ELSEVIER

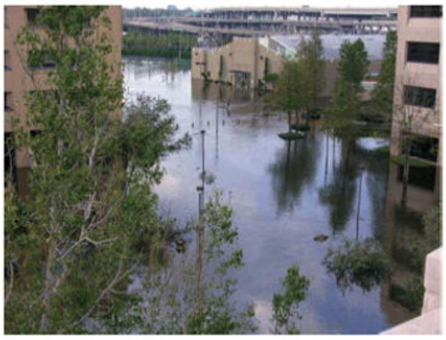
SEPTEMBER/OCTOBER 2007
Volume 14, Number 5

Journal of CHEMICAL Health & Safety

Emergency Management: Disaster Recovery

Glassblowing Safety

Laboratory Chemical Hood Efficiency Opportunities



Hurricane Recovery at Louisiana and Texas Universities

PUBLISHED BY ELSEVIER INC. FOR THE ACS DIVISION OF CHEMICAL HEALTH AND SAFETY

FEATURE

Major energy efficiency opportunities in laboratories—Implications for health and safety

Laboratory facilities present a unique challenge for energy efficient design, partly due to their health and safety requirements. Recent experience has shown that there is significant energy efficiency potential in laboratory buildings. However, there is often a misperception in the laboratory community that energy efficiency will inherently compromise safety. In some cases, energy efficiency measures require special provisions to ensure that safety requirements are met. In other cases, efficiency measures actually improve safety. In this paper we present five major, yet under-utilized, energy efficiency strategies for ventilation-intensive laboratories and discuss their implications for health and safety. These include: (a) optimizing ventilation rates; (b) reducing laboratory chemical hood energy use; (c) low-pressure drop HVAC design; (d) right-sizing HVAC systems; and (e) reducing simultaneous heating and cooling. In all cases, the successful design and implementation of these strategies requires active and informed participation by health and safety personnel.

By Paul A. Mathew, Dale A. Sartor, Geoffrey C. Bell, David Drummond

ENERGY USE AND EFFICIENCY IN LABS

Laboratory facilities present a unique challenge for energy efficient and sustainable design, with their inherent complexity of systems, health and safety requirements, long-term flexibility and adaptability needs, energy use intensity, and environmental impacts. The Department of Energy's CBECS[11] database indicates that laboratories are among the three most energy intensive building types. A single six-foot-wide hood in a laboratory can consume as much energy as three average U.S. homes. Laboratories often require a minimum of 6–12 air changes per hour of outside air. However, laboratory facilities have historically been overlooked by the energy efficiency community, which tended to focus on larger segments of the buildings population, such as offices and retail facilities. Also, laboratories were seen as too specialized and complex to deal with. Efficiency has typically been limited to lighting systems and minor HVAC measures, leaving out the more energy-intensive opportunities.

Recent experience has shown that there is significant energy efficiency potential in laboratory buildings. Table 1 summarizes the energy savings reported in case studies documented by the Laboratories for the 21st Century (Labs21) program. Figure 1 lists some of the significant energy efficiency strategies in laboratories, documented in various Labs21 resources.[6] Some strategies are common to commercial buildings in general (e.g. efficient chillers, lighting, etc.). Others opportunities require special considerations for laboratories (e.g. energy recovery). Finally, some opportunities are very specific to laboratories (e.g. high-performance hoods). Most of these efficiency strategies have health and safety implications. Safety is always the first priority in laboratory design and operation. Energy efficiency measures should always maintain or improve safety relative to standard practice. There is often a misperception in the laboratory community that energy efficiency will inherently compromise safety. In some cases, energy efficiency measures require special provisions to ensure that safety requirements are met. In other cases, efficiency measures actually improve safety. In all cases, the successful design and implementation of these strategies requires active and informed participation by heath and safety personnel.

The purpose of this paper is to describe five significant energy efficiency strategies (underlined items in Figure 1) and their implications for safety. We selected these strategies because they have consistently proven to have a high impact on energy use but are also generally under-utilized. For each strategy, we describe the energy

Paul A. Mathew is affiliated with Lawrence Berkeley National Laboratory, United States (Tel.: 510 486 5116; fax: 510 486 4089; e-mail: PAMathew@lbl.gov).

Dale A. Sartor is affiliated with Lawrence Berkeley National Laboratory, United States.

Geoffrey C. Bell is affiliated with Lawrence Berkeley National Laboratory, United States.

David Drummond is affiliated with University of Wisconsin–Madison, United States.

1871-5532/$32.00
doi:10.1016/j.jchas.2007.01.002

Table 1. Summary of energy savings achieved in case studies documented by the Labs21 Program (See http://www.labs21century.gov/toolkit/case_studies.htm)

Lab name	Location	Lab Type	Size (Gross, sf)	Energy Savings (%)
Donald Bren Hall, University of California	Santa Barbara, CA	Teaching	84,672	50
Fred Hutchinson Cancer Research Center	Seattle, WA	Biological	532,602	33
Georgia Public Health Laboratory	Decatur, GA	Clinical	66,030	36
Kosland Integrated Natural Science Center, Haverford College	Haverford, PA	Teaching	185,423	45
Molecular Foundry, Lawrence Berkeley National Laboratory	Berkeley, CA	Nanotechnology	89,224	25
National Institutes of Health Building 50	Bethesda, MD	Biological	294,532	40
Nidus Center for Scientific Enterprise	St. Louis, MO	Biotechnology	41,233	38
Pharmacia Building Q	Skokie, IL	Chemistry	176,000	40
Process and Environmental Technology Laboratory	Albuquerque, NM	Physical Science and Chemistry	151,435	40
Science & Technology Facility, National Renewable Energy Lab	Golden, CO	Research	71,000	38
U.S. EPA National Vehicle and Fuel Emissions Lab	Ann Arbor, MI	Automotive	135,000	60
Whitehead Biomedical Research, Emory University	Atlanta, GA	Biomedical	184,000	22

Note: Energy savings % is relative to standard design practice for that organization.

efficiency benefits and address how it can be implemented to maintain or improve safety. Following this we also briefly discuss the integrated design process and particularly the role of the health and safety personnel in that process.

"HOW MUCH AIR IS ENOUGH?" – SCRUTINIZE THE AIR CHANGES

Ventilation is often the largest component of energy use in a laboratory. Various codes and standards recommend a wide range of minimum ventilation rates – from 4 to 12 air changes per hour (ACH), as shown in Table 2.

In many laboratories, these minimum ventilation rates are set at excessively high levels even though more air changes does not necessarily improve safety. The challenge is to determine an optimal ventilation rate that both handles the worst credible scenario safely and manages common scenarios efficiently. The Labs21 Best Practice Guide on this topic[13] describes a deliberate decision-making process to optimize ventilation rates. Some of the key techniques are:

- Using lower ventilation rates during unoccupied periods, as suggested in the ASHRAE Laboratory Design Guide.[21]
- Control banding, in which laboratories are classified into control bands that represent different ventilation requirements. The ventilation rate can then be optimized for each laboratory based on its control band, rather than a blanket rate that

Major Efficiency Strategies for Laboratories

Ventilation Systems

- Optimizing ventilation rates
- Minimizing areas requiring high ventilation rates
- High performance fume hoods – VAV, low-volume
- Multi-stack exhaust plenum with staged exhaust fans
- Low-pressure drop design

Heating and Cooling Systems

- Energy recovery (latent and sensible)
- Right-sizing HVAC systems
- Systems that minimize or eliminate reheat
- Multiple cooling loops at different temperatures.
- High part-load heating and cooling efficiency

Lighting Systems

- Daylighting
- High-efficiency electrical lighting systems
- Occupancy controls

Fig. 1. Major energy efficiency strategies in laboratories. Underlined items are discussed in this paper.

Table 2. Minimum ventilation rates prescribed by various standards

Standard	ACH Number
ANSI/AIHA Z9.5[3]	The specific room ventilation rate shall be established or agreed upon by the owner or his/her designee
NFPA-45-2004[22]	Minimum 4 ACH unoccupied, occupied "typically greater than 8 ACH"
ACGIH Ind. Vent 24th ED., 2001[1]	The required ventilation depends on the generation rate and toxicity of the contaminant not on the size of the room in which it occurs
ASHRAE Lab Guide-2001[21]	4–12
OSHA 29 CFR Part 1910.1450[23]	4–12

assumes the highest hazard level in all laboratories.

- Use of computational fluid dynamics (CFD) modeling or tracer gas evaluations to: (a) optimize the configuration of hoods, air registers, and other ventilation system components; (b) estimate residence times of hazards under normal operation as well as spill scenarios; (c) identify "dead spaces" (areas of poor ventilation), and airflow patterns around hoods that may compromise containment.

The use of CFD essentially allows a performance-based approach to configuring the airflow system and ventilation rate in the space, rather than a prescriptive approach. For example, in a new laboratory space for a major pharmaceutical company, the health and safety officer defined a spill scenario, which was then modeled at different room air change rates using CFD. The results showed that there was practically no difference in spill clearance times between 8 ACH and 12 ACH for the lab analyzed.[18] Careful design of the air supply improves both spill clearance and, as previously noted, also improves laboratory chemical hood capture.

Some designers recommend systems with emergency overrides to provide higher ventilation rates during a spill, but reduced ventilation rates during normal operation. In theory, this reduces both energy use and first cost compared to designing for continuous operation under rare worst-case conditions. However, major spills in laboratories are uncommon and, as the preceding paragraph notes, even a 50% increase in air exchange rate may have little effect on spill clearance time. In addition, an emergency override requires reducing design credits for diversity[a] to prevent an override in one laboratory from causing unsafe airflow rates in other laboratories.

Health and safety personnel have an especially critical role in successfully implementing these techniques. First of all, it is essential that they are properly integrated into the design decision-making process, as discussed later. Secondly, they should be challenged to review and reconsider existing standards that may be unnecessarily high (for example, they should try to define a scenario where 10 ACH is safe but 6ACH is not). They should use their best judgment and risk management expertise to define hazard scenarios, hazard thresholds and other criteria for the design team to optimize ventilation rates based on the best science available.

"TAME THE HOODS" – REDUCE HOOD ENERGY USE

In many laboratories, laboratory chemical hoods are the dominant factor in overall energy use. In addition to the fan energy, they also consume large amounts of energy used to heat and cool the air they exhaust. Laboratory chemical hood energy use can be reduced by programmatic as well as technological strategies.

Reduce the number and size of hoods

New labs often standardize on a single hood size (increasingly larger) and install more than needed to allow for growth and flexibility. Existing facilities often have labs needing hoods, while many other labs have under-utilized hoods. Energy management should begin with a careful review of hood use and requirements. Specifically:

- Install only hoods needed immediately.
- Encourage the removal of under-utilized hoods.
- Encourage the use of hoods as a shared resource.
- Promote the use of ventilated storage cabinets. Hoods should only be used for experimental procedures, not for storage. Typically, one laboratory chemical hood uses as much energy as more than 200 ventilated storage cabinets (see Figure 2).
- Promote the use of low-air-flow alternatives to hoods where appropriate (e.g. snorkels and dedicated equipment exhausts).

It is helpful to remind users that hoods serve the dual purpose of ventilation and protection against splash and flying glass in case of an accident. Weighing, pouring, storing odorous materials and containing sources of heat and water vapor require exhaust ventilation but usually do not require protective containment. Users should be provided information on ventilation alternatives and the potential capital and operating savings they offer. Even users who profess to ignore operating costs because "someone else pays," are motivated to control capital costs, which the users can often redirect to purchase additional equipment.

To allow for flexibility and future growth, it's important to size the air distribution ductwork system for ample capacity. Additionally, tees, valves, and pressure controls in the distribution ductwork should be

[a] Diversity is defined and discussed in Section "Use VAV hoods with effective sash management".

Fig. 2. These ventilated storage cabinets at the University of Wisconsin–Madison collectively require only 5% of the energy use of a single hood.

designed for easy additions and removals. This will help provide for future flexibility with minimal impact on initial costs. Generously sized ductwork will also provide energy efficiency by virtue of lower pressure drop, as discussed later.

In order to make these tactics effective, health and safety personnel need to ensure that users are properly trained on the appropriate use of laboratory chemical hoods, ventilated storage cabinets, snorkels, and other exhaust devices. Simply providing excess number of hoods does not improve safety.

Restrict the sash opening

In an effort to maintain 100 fpm face velocity, hood designs have been developed to simply reduce or restrict the sash opening and thus save energy. The two most popular techniques are vertical sash stops and horizontal sliding sashes.

Sash stops prevent a vertical sash from opening all the way. Usually the stops are placed at 18 in. thus blocking the sash from fully opening. In most cases the stops are designed for easy override to lift the sash higher during experimental setup. Systems designed for the 18 in. opening can violate Cal/OSHA standards when the sash stops are bypassed.[9] In all cases, this calls for a sash management culture that assures bypass only when hazards are not present.

Horizontal sliding sashes are used to protect the user by restricting the hood opening. In theory, sliding sashes cannot be opened all the way but two or more can overlap, creating an opening. Users often feel the sashes get in the way and may possibly remove them, which compromises safety and efficiency. Further, the sashes' sharp edges can cause airflow turbulence, which may result in spillage from the hood. Nevertheless, organizations with strong sash management cultures have successfully used this design feature.

Use two-speed hoods

A laboratory chemical hood with no one present does not need the same airflow as one with a person at or near its face because there are fewer sources of turbulence. Control companies offer an occupancy sensor based two-position control that reduces the face velocity from 100 fpm to around 60 fpm when no one is present. These systems are often marketed as a substitute for variable air volume (VAV) hoods but they can be combined with VAV hoods and other technologies. They have a lower cost (than VAV hoods) and they assure some savings even when the sash is left open. Therefore, in an environment of poor sash management, two-speed hoods can save more energy than VAV hoods.

When operating at reduced face velocity, hoods are more susceptible to interfering air currents (note that cross drafts must be reduced when operating at reduced face velocity). Therefore, heat sources must be at least one foot (30 cm) into the hood to avoid compromising the effectiveness of the hood.

Use VAV hoods with effective sash management

VAV laboratory chemical hood systems control the airflow to maintain a constant face velocity. As the sash is closed, the exhaust air volume is automatically decreased. In a VAV system, energy savings occur when a sash is less than fully open, which reduces exhaust flow while maintaining a constant face velocity. No energy is saved if the hood sashes are left wide open. Each hood user must operate the sash properly to ensure that the system achieves full energy savings potential. Energy and safety goals are synergistic with VAV hoods – a closed hood is much safer than an open hood. Furthermore, a VAV system dynamically controls the face velocity to the required level.

When designing a lab that will have VAV hoods, a diversity-factor, i.e., the ratio of minimum-to-maximum airflow, can be used to help "right-size" the HVAC system to reduce first-cost and increase operating efficiency. For example, if all the hoods were running at half the design airflow, it would represent 50% diversity. Importantly, there is a safety consequence when estimating a diversity-factor. The most conservative designers assume all the hoods are open when sizing their equipment, which is a 100% diversity-factor (minimum flow equals maximum flow). Other designers will more aggressively use a 50% diversity-factor. Estimating a diversity-factor depends, in part, on the number of hoods (a greater potential for diversity is assumed with larger numbers of hoods). Health and safety personnel should help designers determine the facility's diversity-factor, taking into account the number of hoods, their usage patterns, and other factors.

VAV hood installations require a strong sash management plan that includes periodic training and awareness, informational placards, and possibly penalties and rewards for proper use. A study at Duke University showed that simple user training improved sash management by over 30% – from 5% of the time closed to 39% of the time closed.[7] The sash management plan should be incorporated in the Chemical Hygiene Plan for the laboratory.

Closed sashes on VAV hoods can yield remarkable savings. For example, consider a building with 100 laboratory chemical hoods, a conservative operating cost of $3,000 per year with fully open sash and airflow reduced to 25% of full flow with sash closed. Under those assumptions, if users left 25 sashes open after work, the owner could pay someone $30,000 per year to walk the building each evening and close the sashes and still have a few thousand dollars profit.

In response to poor sash management, several companies have introduced automated sash closure systems. An auto sash closure system coupled with a VAV hood control system can be an effective energy saving strategy, since most hoods are "occupied" only a few hours a week.[12] Much higher diversity assumptions could be made with such a system, potentially reducing first cost.[b]

A frequent problem of VAV hoods is that they require changes in maintenance procedures that owners fail to address. Systems with airflow sensors need periodic cleaning and all VAV systems require relatively frequent and detailed checks to assure continued proper operation when compared with constant velocity systems. Constant velocity systems generally fail completely when they fail, for example, when a motor or drive belt fails. Even improperly calibrated alarms will usually detect complete failure. However, a control failure or improper calibration of a VAV hood may cause increased airflow, which is a waste of resources, or reduced airflow, which creates a safety hazard. Alarms are less likely to react to these smaller changes and, in many cases, a calibration error will affect the alarm as well as system performance. Modern good practice requires that hoods have monitoring devices to detect excessively high or low airflow. The devices provide immediate warning to the user in case of fan or control failure. The monitoring devices require periodic testing and calibration and are not a substitute for routine system testing and maintenance. Facilities organizations are beginning to recognize that all types of laboratory ventilation systems need periodic rebalancing in addition to checks of individual hoods.

[b] As a cautionary note, owners should also be careful not to overestimate savings from sash management strategies, by automatically assuming a worst-case baseline of 0% sash closure i.e. hoods open 100% of the time.

Consider high performance low-volume hoods

As the number of hoods in a typical laboratory decreases, designers will encounter more locations in which a VAV hood at minimum flow exhausts less air than the minimum established for the room. In these cases, a high performance low-volume hood or even a conventional hood may be an appropriate and less costly choice without compromising energy conservation goals. Several high performance low-volume hoods are on the market. These hoods generally use alternative airflow mechanisms to maintain containment of contaminants within the hood at reduced exhaust volumes. High-performance low-flow laboratory chemical hoods offer a number of potential advantages over VAV, including simplicity in design, installation and maintenance (generally constant volume with no diversity assumptions required), lower peak requirements, safety, and the ability to downsize the mechanical/electrical systems.

One of the safety benefits of high performance hoods is that the design of the front airfoil forces work to be done further back in the hood where capture is inherently better. Safety concerns with high-performance hoods usually have to do with the lower face velocities. Whether real or perceived, these concerns are best mitigated by effective commissioning, including containment testing using the ASHRAE 110 method of testing.[4] For example, smoke and containment testing for the Berkeley Hood (Figure 3) indicated excellent performance and containment in compliance with the ASHRAE-110 procedures and ANSI Z9.5 leakage thresholds.

Unpublished tests at the University of Wisconsin–Madison have shown excellent ASHRAE-110 performance at face velocities as low as 60 fpm with several currently marketed low-flow hoods. However, the current ASHRAE test is a static test that makes no allowances for sudden user movements, equipment arrangements in the hood or conditions of final installation, hence the importance of commissioning. Consideration of these variations may lead to selection of a higher face velocity.

At flow rates of 60–100 fpm, depending on conditions, laboratory chemical hood performance is affected as much by the design of the air supply as by face velocity. An increase in hood face velocity requires a concurrent increase in room airflow and air exchange rates if other conditions are held constant. Under constant conditions, research has shown that increased hood face velocity above some acceptable minimum does not improve contaminant capture because of the increase in supply air turbulence.[10]

"DROP THE PRESSURE" – LOW-PRESSURE DROP DESIGN

The energy used by the supply and exhaust fans in a laboratory ventilation system is a function of three variables: (a) efficiency of the fan motor and drive system; (b) the volume of air moved by the fan system; and (c) the system static pressure, all of which determines how much fan power is needed. Of these three, lowering the static pressure typically offers the greatest potential for energy savings in the ventilation system. Despite the huge impact of the ventilation system on yearly energy consumption, it is not uncommon to see laboratory buildings with a total of 8–12 in. w.g. pressure drop for the supply and exhaust system combined. Careful ductwork layout and component selection throughout both supply and exhaust system design can lower the total pressure-drop significantly.[14,24] Some of the key techniques[c] are:

- Lower face velocity heating and cooling coils and filters throughout the system.

[c] The ACGIH Industrial Ventilation Guide and ANSI Z9.2-2001[2] are additional sources for design help.

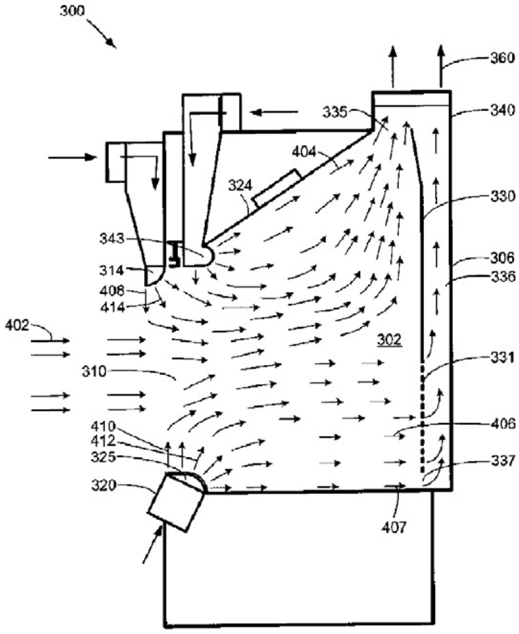


Fig. 3. Lawrence Berkeley National Laboratory has developed the "Berkeley Hood"—a low-flow laboratory chemical hood using a "push–pull" approach that reduces airflow 50–75% relative to a standard hood.[5] For the push, low volume air fans deliver conditioned lab air, supplying inside and outside plenums above the sash and supplying a perforated air foil below. The pull is supplied by the standard exhaust fan sized to draw the appropriate amount of air.

- Rationalized duct layout that minimizes bends, and uses radius rather than square bends.
- Larger, round ductwork.
- System design that minimizes or eliminates the need for noise control devices.
- Lowering pressure drop of heat recovery devices and VAV control devices.
- Multi-stack exhaust system with staged fan control.

Although VAV systems inherently reduce pressure drop during non-peak loads by reducing the airflow volume, designers using VAV systems should still consider these techniques. Sizing for low-pressure drop under peak conditions also provides significant flexibility to add load to the system in the future. Also, some laboratories (e.g., at the University of California) are as concerned about controlling peak demand as saving energy. Table 3 compares standard, good and better practice for low pressure drop design, indicating that fan power can be reduced to 1/3 of standard design.

Incorporating high-performance low airflow hoods into the design will further reduce pressure drop and fan power requirements.

Low-pressure design needs to be used cautiously in larger buildings because pressure changes within the building caused by wind infiltration are more likely to affect the system. VAV systems will self-adjust to compensate and modern buildings are much less permeable than older buildings. Nonetheless, predictive modeling and zoned designs should receive serious consideration.

"GET REAL WITH PLUG LOADS" – RIGHT-SIZING HVAC SYSTEMS

Equipment loads in laboratories are frequently overestimated because designers often use estimates based on "nameplate" rated data, and design assumptions of high utilization. This results in oversized HVAC systems, increased initial construction costs, and increased energy use due to inefficiencies at low part-load operation. Recent studies at the University of California at Davis are illustrative of the extent of over-sizing (see Figure 4).

There are several techniques to obtain better estimates of equipment loads and right-size HVAC systems.[15,19] Some of these include:

- Measuring equipment loads in a comparable laboratory during peak activity, and then sizing HVAC and electrical systems based on these data.
- Use of a probability-based "bottom-up" approach to more accurately assess load diversity in a structured, methodical manner.
- Configuring equipment for high part-load efficiency.
- Negotiating risk management between owners and designers.

Right-sizing is a powerful strategy in that it reduces both first costs and life-cycle costs, as demonstrated in the Molecular Foundry at Lawrence Berkeley National Laboratory. The design team measured actual loads in three other laboratory buildings at the LBNL campus, and the electrical and mechanical systems were downsized by roughly one-third, resulting in a savings of about $2.5 million, over 4% of the construction cost.

Table 3. Standard, good and better practice for low pressure drop design[24]

Component	Standard	Good	Better
Air handler face velocity	500	400	300
Air handler pressure drop	2.5 in. w.g.	1.7 in. w.g.	0.75 in. w.g.
Energy recovery device pressure drop	1.00 in. w.g.	0.60 in. w.g.	0.35 in. w.g.
VAV control devices pressure drop	Constant volume, N/A	Flow measurement 0.60–0.30 in. w.g.	Pressure difference 0.10 in. w.g.
Zone temperature control coils pressure drop	0.5 in. w.g.	0.30 in. w.g.	0.05 in. w.g.
Total supply and exhaust ductwork pressure drop	4.0 in. w.g.	2.25 in. w.g.	1.2 in. w.g.
Exhaust stack pressure drop	0.7 in. w.g. full design flow through entire exhaust system, CV	0.7 in. w.g. full design flow through fan and stack only, VAV with bypass	0.75 in. w.g. averaging half the design flow, VAV system with multiple stacks
Noise control (silencers)	1.0 in. w.g.	0.25 in. w.g.	0.0 in. w.g.
Total	9.7 in. w.g.	6.2 in. w.g.	3.2 in. w.g.
Approximate fan power requirement (W/cfm)[a]	1.8	1.2	0.6
Using the above data, consider a 25 ft × 40 ft × 10 ft laboratory with 6 air changes per hour (1,000 cfm) and electricity at $.08 per kWh			
Annual savings for one lab	$0	$419	$840
25 yr life cycle svgs for building with 20 labs (present value)	$0	$131,000	$262,000
CO_2 emissions avoided (tons)	0	1,829	3,658

[a] To convert pressure drop values into the commonly used metric of W/cfm, these assumptions were used in the fan power equation: 0.62 fan system efficiency (70% efficient fan, 90% efficient motor, 98% efficient drive).

Right-sizing of HVAC systems does not directly impact health and safety. The primary concern is that laboratories may get more energy intensive equipment than initially anticipated and the right-sized systems will not be able to handle the extra thermal load – which will cause user comfort problems. This risk can be mitigated by incorporating modular systems that allow for additional cooling capacity to be added, if necessary.

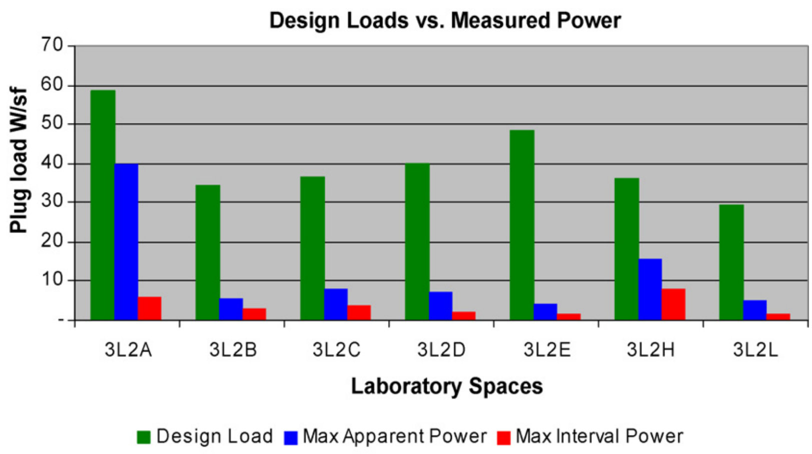


Fig. 4. Comparison of design loads and measured plug loads in various laboratory spaces at the University of California at Davis. Measurements were taken over a 2-week period while labs were fully occupied. Max apparent power is the measured peak (instantaneous) apparent power. Max interval power is the peak interval power (power averaged over 15 min interval).

"JUST SAY NO TO REHEAT" – ELIMINATE SIMULTANEOUS HEATING AND COOLING

Over-sizing is only one of the problems resulting from incorrect estimation of equipment loads. The other major problem is the under-estimation of load variation across different laboratory spaces, which in turn exacerbates the problem of simultaneous heating and cooling, particularly for systems that use zone reheat for temperature control. Figure 5 shows the range of 15-min interval power for various laboratory spaces in the UC Davis laboratory building referenced earlier. This is a fairly common situation, where one or two labs have very high equipment

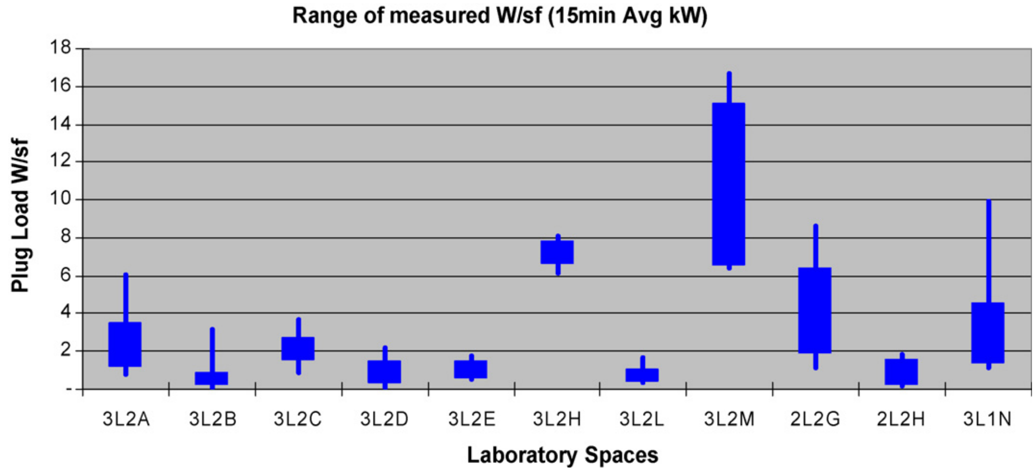


Fig. 5. Range of measured 15-min interval power (W/sf) for various laboratory spaces in a building at UC Davis. The upper and lower ends of the lines represent maximum and minimum respectively. The upper and lower ends of the boxes represent 99th and 1st percentiles of the measurements respectively.

loads compared to the others. The problem arises when all these labs are served by a single air-handling unit with zone reheat coils for temperature control (a widely used HVAC strategy). The high-intensity labs then drive the supply air temperatures and flows to handle their high equipment loads, and as a result, all the other labs have to use more reheat to maintain desired temperatures. Some of the techniques to minimize simultaneous heating and cooling include the following[16,20]:

- Properly assess load variation during the design process and design HVAC systems that accommodate the variations – designers should not assume uniform loads across the labs.
- Consider alternative HVAC systems that can mitigate reheat energy use by separating the thermal and ventilation systems. For example, a dedicated ventilation air stream can provide tempered air while fan coils or radiant panels provide additional thermal conditioning within the zone.
- Continuous commissioning and diagnostics can help to identify zones with excessive reheat, and to adjust system control and operation accordingly.

Note that implementing a fan coil in a lab space requires coordination with and education of health and safety and facility personnel and local authorities to determine if there are prohibitions in the local codes on air re-circulation within laboratory spaces. A properly implemented fan-coil system will not mix air between any adjacent zones and will have no impact on space pressurization and ventilation rates. While it does not violate the intent of most code regulations, this approach may be unfamiliar and may require educating and gaining the approval of code officials. The facilities organization may be concerned about the maintenance requirements of fan coil units, especially if their only experience is with older units. This system was a key energy efficiency feature of the Natural Science Center at Haverford College.[8] During the summer, no heat is used by the system (the heating supply is shut off) – it is therefore a system that literally does not use any reheat. For more information on this building, see the Labs21 case study.[17]

INTEGRATING SAFETY AND EFFICIENCY IN THE DESIGN PROCESS

It is now widely recognized by architects and engineers that an integrated design process is critical to a safe and energy-efficient design. Efficiency cannot be effectively accomplished by simply adding a slew of energy efficient features to an otherwise standard design. Rather, an integrated design process takes advantage of the synergies between different strategies in order to obtain a cost-effective, safe and efficient design. An integrated design process actively engages all the key stakeholders early in the design process. This includes owners, users, architects, engineers, facilities personnel and commissioning agents. In the case of laboratories, this should also include laboratory consultants and health and safety personnel. Efficiency strategies and their safety implications should be considered right from the programming phase and conceptual design. If health and safety personnel are brought in only during design development or worse, during final design review, they may raise objections that may require significant revisions, delaying the project and driving up costs. Health and safety personnel need to participate in the process as partners rather than "safety police". This ensures that efficiency and safety objectives can be optimized and met in a cost-effective manner.

ACKNOWLEDGEMENTS
The authors would like to acknowledge the Labs21 Program, sponsored by the US Department of Energy and the US Environmental Protection Agency, for its support in developing the content of this article.

REFERENCES

1. ACGIH. *Industrial Ventilation: A Manual of Recommended Practice* – 24th ed. The American Conference of Governmental Industrial Hygienists, Inc. (ACGIH), eds. Cincinnati, OH. ISBN: 1-882417-42-9, 2001.
2. ANSI/AIHA, Z9.2-2001. *Fundamentals Governing the Design and Operation of Local Exhaust Ventilation Systems*, American National Standards Institute, Inc./American Industrial Hygiene Association.
3. ANSI/AIHA Z9.5-2003. *American National Standard for Laboratory Ventilation*, American National Standards Institute, Inc./American Industrial Hygiene Association.
4. ASHRAE. *ASHRAE/ANSI Standard 110: Method of Testing Performance of Laboratory Fume Hoods.* American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, Georgia, 1995.
5. Bell, G.; Sartor, D.; Mills, E. *The Berkeley Hood: Development and Commercialization of an Innovative High-Performance Laboratory Fume Hood*, A Progress and Research Status: 1995 – September 2003. Lawrence Berkeley National Laboratory Report LBNL-48983 (rev.), 2003. Available at: http://ateam.lbl.gov/hightech/fumehood/Publications.html.
6. Bell, G. C.; Mills, E.; Sartor, D.; Avery, D.; Siminovitch, M.; Piette, M. A. *A Design Guide for Energy-Efficient Research Laboratories, LBNL-PUB-777*. Lawrence Berkeley National Laboratory, Center for Building Science, Applications Team, September 1996–2003.
7. Brewer, B. *Quantification of Incremental Energy Savings Related to Hood Sash Best Management Practices*, Presentation at 2003 Labs21 Annual conference, Denver, Colorado, October 2003.
8. Bartholomew, P. Saving energy in labs. *ASHRAE J.* **2004,** 35–40.
9. CAL/OSHA Standard 5154.1 Ventilation Requirements for Laboratory-Type Hood Operations.
10. Caplan, K. J.; Knutson, G. W. Influence of room air supply on laboratory hoods. *Am. Ind. Hyg. Assoc. J.* **1982**, *43*(10), 738–746.
11. Energy Information Administration. *Commercial Buildings Energy Consumption Survey*, 2003. Available on the web at: http://www.eia.doe.gov/emeu/cbecs/contents.html.
12. Greenley, P. L.; DiBerardinis, L. J.; Lorch, F. A. *Containment Testing for Occupied and Unoccupied Laboratory Chemical Hoods*. ASHRAE Transactions: Symposia, Winter Meeting, Chicago, IL, CH-99-9-1, 1999.
13. Labs21. *Optimizing Ventilation Rates in Laboratories*, Pending publication by Laboratories for the 21st Century Program, 2006. Draft available from authors.
14. Labs21. *Low Pressure Drop Design for Laboratories*, Published by Laboratories for the 21st Century Program, 2005. Available at: http://www.labs21century.gov/toolkit/bp_guide.htm.
15. Labs21. *Right-sizing Laboratory Equipment Loads*, Published by Laboratories for the 21st Century Program, 2005. Available at: http://www.labs21century.gov/toolkit/bp_guide.htm.
16. Labs21. *Minimizing Reheat Energy Use in Laboratories*, Published by Laboratories for the 21st Century Program, 2005. Available at: http://www.labs21 century.gov/toolkit/bp_guide.htm.
17. Labs21. *Marian E. Koshland Integrated Natural Science Center*, Published by Laboratories for the 21st Century Program, 2005. Available at: http://www.labs21century.gov/toolkit/case_studies.htm.
18. Maine, G.; Frei, S.; Shwartz, W. *Modeling Laboratory Design: An Integrated Process*, Presentation at 2002 Labs21 Annual conference, Durham, North Carolina, October 2002. Available at: http://www.labs21century.gov/conf/past/2002/abstracts/e3_maine.htm.
19. Mathew, P.; Greenberg, S.; Frenze, D.; Morehead, M.; Sartor, D.; Starr, W. *Right-sizing Laboratory HVAC systems – Part 1 HPAC Engineering*, September 2005.
20. Mathew, P.; Greenberg, S.; Frenze, D.; Morehead, M.; Sartor, M.; Starr, W. *Right-sizing Laboratory HVAC systems – Part 2 HPAC Engineering*, October 2005.
21. McIntosh, I. B. D.; Dorgan, C. B.; Dorgan, C. E. *ASHRAE Laboratory Design Guide*, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA, 2001.
22. NFPA-45-2004. National Fire Protection Association.
23. OSHA 29 CFR 1919–1450 Appendix C. Occupational Safety and Health Administration, 1990.
24. Weale, J.; Rumsey, P.; Sartor, D.; Lock, L. E. Laboratory low-pressure drop design. *ASHRAE J.* **2002**.